Technical Article

Evaluation of Airborne Thermal Infrared Imagery for Locating Mine Drainage Sites in the Lower Youghiogheny River Basin, Pennsylvania, USA

James I Sams III[1], Garret A. Veloski[2], Terry E. Ackman[2]

[1]USGS, Water Resources Disc, Pittsburgh, PA, USA, e-mail: jisams@usgs.gov; [2]NETL, US DOE, Pittsburgh, PA, USA

Abstract. Nighttime high-resolution airborne thermal infrared imagery (TIR) data were collected in the predawn hours during Feb 5-8 and March 11-12, 1999, from a helicopter platform for 72.4 km of the Youghiogheny River, from Connellsville to McKeesport, in southwestern Pennsylvania. The TIR data were used to identify sources of mine drainage from abandoned mines that discharge directly into the Youghiogheny River. Image-processing and geographic information systems (GIS) techniques were used to identify 70 sites within the study area as possible mine drainage sources. The combination of GIS datasets and the airborne TIR data provided a fast and accurate method to target the possible sources. After field reconnaissance, it was determined that 24 of the 70 sites were mine drainage. This paper summarizes: the procedures used to process the TIR data and extract potential mine-drainage sites; methods used for verification of the TIR data; a discussion of factors affecting the TIR data; and a brief summary of water quality.

Key words: Abandoned mine lands; acid mine drainage; thermal infrared imagery

Introduction

The Youghiogheny River Basin includes a drainage area of 4,566 km^2 in western Maryland, northeastern West Virginia, and southwestern Pennsylvania. The Youghiogheny River joins the Monongahela River near McKeesport, PA (Figure 1). The basin lies within the Appalachian Plateau physiographic province and contains sedimentary rocks of Mississippian and Pennsylvanian age. The Youghiogheny River Basin was recognized for its coal resources as early as 1770. Approximately 60 % of the basin is underlain by bituminous coal, a major natural resource for the economy of the area. From small operations in the early 1800s, coal production expanded greatly after the industrial revolution of the late 19th century. Coal has been mined from the Pittsburgh, Redstone, Sewickley, Freeport, Kittanning, Bakerstown, and Brush Creek coal beds. The most significant coal bed in the basin is the Pittsburgh coal seam, which has been referred to as the most valuable minable deposit in the world because of its use in the iron and steel industry (Edmunds and Koppe 1968). In this region, surface- and underground-mining techniques were both used. During the late 1800s, coking centers developed along the river at cities like Connellsville and Star Junction (Mackin Engineering 1997). Between 1860 and 1919, western Pennsylvania was a world leader in bituminous coal mining and steel production. In 1918, coal production peaked in Pennsylvania at 177 million tons per year. Coal production in the lower Youghiogheny River Basin has been decreasing steadily since the early 1940s (Pennsylvania Coal Association 1995) (Figure 2). Today, the region is no longer a booming coal and steel-making center. More and more, the river is being used for recreation. For example, the 69 km Youghiogheny River Trail, a multi-use recreational trail built on the banks of the river between McKeesport and Connellsville, attracts 200,000 to 300,000 people annually (Mackin Engineering 1997).

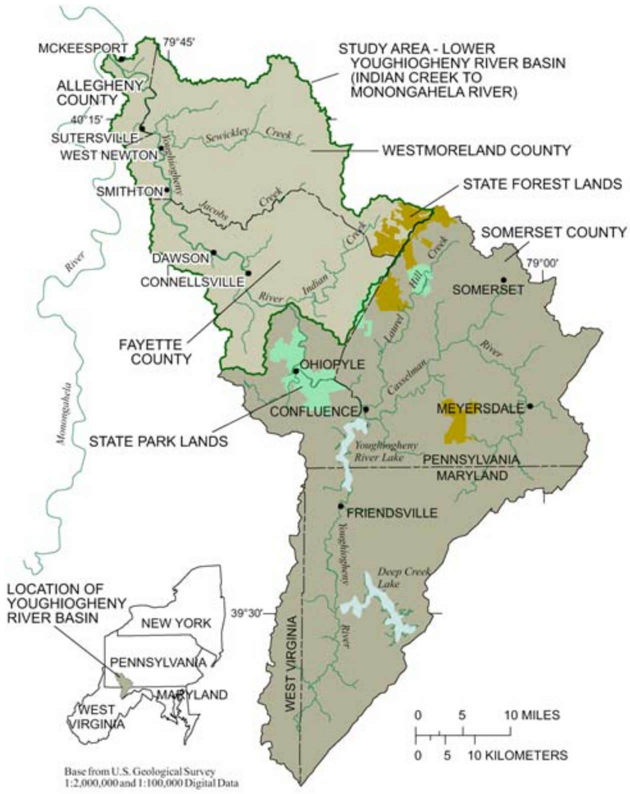

Figure 1. The Youghiogheny River Basin and location of the study area in Pennsylvania

However, in many areas along the river, mine drainage contributes elevated concentrations of acidity, sulfate, and metals that detract from the aesthetic quality of the river and impair aquatic biota and habitat.

Drainage from abandoned mines is the biggest source of surface water-use impairment in the river basin. Approximately 147 abandoned mine land (AML) sites exist within the Lower Youghiogheny River basin (U.S. Office of Surface Mining 1998). A study of sulfate loads and yields in the Allegheny and Monongahela River Basins by Sams and Beer (2000) found that the Youghiogheny River contributed 184,000 t of sulfate (an indicator of mine drainage) to the Monongahela River for the 1980 water year or 14% of the load of total sulfate transported by the Monongahela River. The sulfate yield of the Youghiogheny River was 41.7 t/yr/km^2 of drainage area. By comparison, the sulfate yield for unmined basins was approximately 10 t/yr/km^2.

Local conservation groups, watershed associations, and government agencies are developing plans to correct environmental problems such as mine drainage. The success of these remediation plans hinges on the complete knowledge of all pollution sources within a watershed area. Locating sources of mine drainage in remote areas can be very time consuming. Methods, such as remote sensing, reduce costs and improve efficiencies in detection of mine-drainage sites on a watershed scale.

The study area of this project was the mainstem of the Lower Youghiogheny River (Figure 1). The study area covers 72.4 km of the river, from Connellsville to McKeesport. Twenty-one named tributaries enter the river within this reach. This project evaluated the use of airborne thermal infrared (TIR) imagery for identifying sources of mine drainage that discharge directly to the Youghiogheny River. Combining TIR with image processing and geographic information system (GIS) technology greatly increased the probability of locating mine discharges and other sources of water pollution. However, field inspection was still required to determine whether the thermal feature was mine drainage. Results from this study provided accurate locations of mine drainage along the Lower Youghiogheny River for resource assessment and remediation planning by the watershed associations and the Pennsylvania Department of Environmental Protection (PADEP).

Previous Investigation

In October 5-7, 1998, a chemical synoptic survey was conducted by the U.S. Geological Survey (USGS)

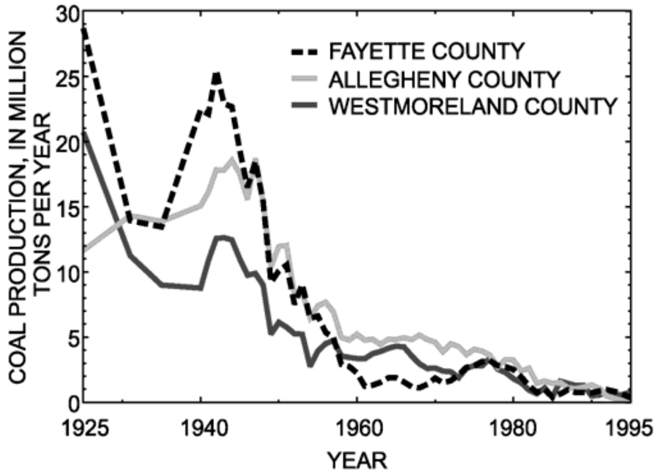

Figure 2. Historical coal production in the three Pennsylvania counties that compose the Lower Yougiogheny River basin, 1925-95 (Pennsylvania Coal Association 1995)

and the U.S. Dept of Energy (DOE) National Energy Technology Laboratory (NETL) to examine water quality in the Lower Youghiogheny River Basin (Sams et al. 2001). Water was sampled at 12 main-stem sites from Connellsville to McKeesport, from 22 tributary streams, and from four mine discharges flowing directly into the river (Table 1, Figure 3). Field crews sampled water from these 38 sites when low-flow conditions prevailed uniformly throughout the study area. Streamflow, specific conductance, water temperature, pH, and dissolved oxygen were measured at each site, and concentrations of major ions and trace elements were measured in the laboratory. The water sampling was designed to identify sources of contaminants from mining operations.

The data were processed and analyzed to mass balance streamflow and chemical loads, in particular sulfate loads, to identify river reaches with unaccounted-for gains and losses in streamflow or sulfate loads. Sulfate is a good indicator of mine drainage because it generally remains conserved in the drainage system (Hem 1985).

Sulfate concentrations in the Youghiogheny River steadily increased from 33 mg/L at Connellsville to 77 mg/L near McKeesport. Approximately 25% of the sulfate load was unaccounted for. Most of the unaccounted-for gains in sulfate loads were between Smithton and McKeesport (Figure 4). The synoptic survey was successful in identifying reaches of the Youghiogheny River where unaccounted-for loads of constituents associated with mining activities were entering the river. However, the survey was not able to locate the source of these mine discharges.

Methods of Current Investigation

Thermal Imagery

Two-band nighttime TIR was acquired along the Lower Youghiogheny River in order to identify point sources of mine drainage that discharge directly to the mainstem. The imaged area included 72.4 km of the Youghiogheny River from Connellsville to McKeesport. The area also included the right and left bank of the river for an average flight width of 350 m. The average width of the river is 85 m.

The TIR was acquired using a Daedalus AADS 1268 12-channel multispectral scanner. Channels 11-12 were alternatively configured for dual thermal operation with sensor spectral sensitivity ranges of 3.10-4.80 μm (band 1) and 8.20-10.50 μm (band 2). The scanner data were corrected for geometric distortion using a combination inertial and differential global positioning system (DGPS) navigation data collected during flight. The DGPS system consisted of a Trimble 4000 rover unit that received position correction information from GPS base station units on the ground. Trajectory data from a Litton LN-200 inertial measurement unit were used to record the orientation of the sensor head. The raw scanner data were post-processed by NETL using a combination of in-house and commercial software.

Table 1. Main-stem, tributary, and mine-discharge sampling sites for the Lower Youghiogheny River Basin synoptic survey, Pennsylvania, October 5-7, 1998[--, not applicable]

Site identifier	Latitude ºN	Longitude ºW	Stream name	Location	Drainage area (km^2)
			river sites		
YR_A	395803	793043	Youghiogheny	Upstream from Indian Creek	2,953
YR_B	400103	793538	Youghiogheny	At USGS gaging station, Connellsville	3,445
YR_C	400118	793551	Youghiogheny	At Rt.119 bridge, Connellsville	3,445
YR_D	400221	793744	Youghiogheny	Downstream Rt. 119 Bridge, 100 m	3,445
YR_E	400210	793805	Youghiogheny	Downstream of site YR_D, 100 m	3,445
YR_F	400244	793935	Youghiogheny	At Rt. 819 Bridge, Dawson	3,548
YR_G	400518	794349	Youghiogheny	At Rt. 4038 Bridge, Layton	3,652
YR_HA	400926	79441	Youghiogheny	At Rt. 981 Bridge, Smithton	3,937
YR_HB	400926	79441	Youghiogheny	Downstream of YR_HA, 100 m	3,937
YR_I	401240	794610	Youghiogheny	At Rt. 136 Bridge, West Newton	3,963
YR_J	401424	794824	Youghiogheny	At USGS gaging station, Sutersville	4,429
YR_K	401846	794942	Youghiogheny	At Rt. 48 Bridge, Boston	4,507
			Tributary sites		
TR_1	395807	793048	Indian Creek	Near mouth	324
TR_2	395858	793507	Laurel Run	Near mouth	4.71
TR_3	400008	793556	Dunbar Creek	Near mouth	95.6
TR_4	400055	793526	Connell Run	Near mouth	8.11
TR_5	400110	793618	Opossum Run	Near mouth	18.6
TR_6	400125	793558	Mounts Creek	Near mouth	80.8
TR_7	400250	793632	Galley Run	Near mouth	8.44
TR_8	400233	793842	Hickman Run	Near mouth	6.73
TR_9	400234	793748	Dickerson Run	Near mouth	15.7
TR_10	400300	793952	Smiley Run	Near mouth	7.02
TR_11	400341	7940048	Laurel Run	Near mouth	7.54
TR_12	400242	794125	Furnace Run	Near mouth	8.21
TR_13	40342	794233	Virginia Run	Near mouth	12.2
TR_14	400509	794403	Washington Run	Near mouth	20.1
TR_15	400721	794518	Browneller Run	Near mouth	5.02
TR_16	400735	794429	Jacobs Creek	Near mouth	245
TR_17	401043	794645	Cedar Creek	Near mouth	14.8
TR_18	401351	794639	Sewickley Creek	Near mouth	435
TR_19	401336	794721	Pollock Run	Near mouth	20.9
TR_20	401433	794824	Gillespie Run	Near mouth	23.5
TR_21	401757	794715	Crawford Run	Near mouth	5.10
TR_22	401925	795021	Long Run	Near mouth	34.2
			Mine discharges flowing directly into the Youghiogheny River		
MD_2	400239	793613		At mine discharge	
MD_3	400235	793628		At mine discharge	
MD_4	400221	793741		At mine discharge	
MD_7	400242	793619		At mine discharge	

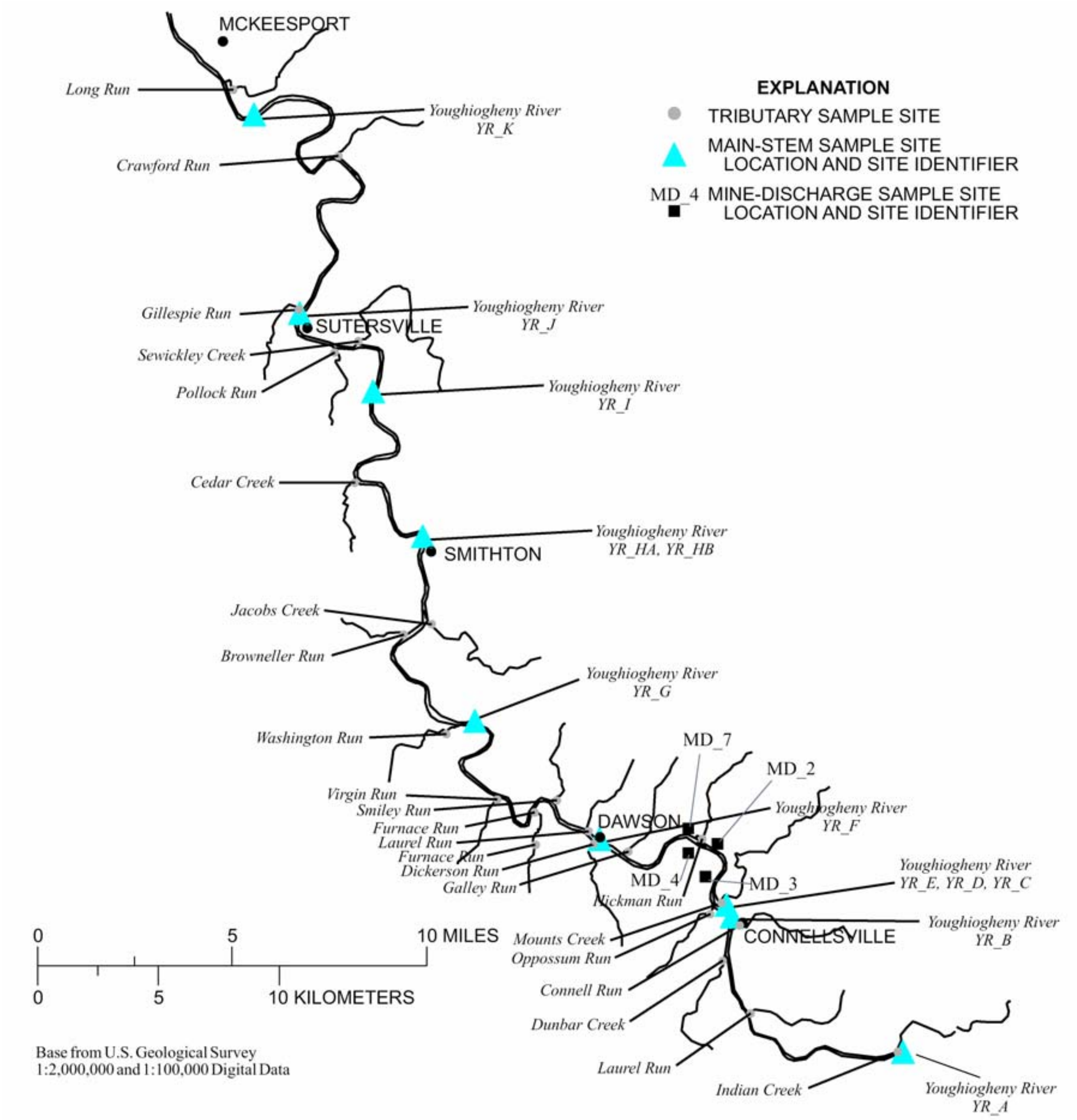

Figure 3. Locations of main-stem, tributary, and mine discharge sampling sites in the Lower Youghiogheny River Basin, Pennsylvania, Oct 5-7, 1998

Typically, TIR imagery consists of airborne scanner data rectified in a rudimentary sense to compensate for aberrations induced by variations in aircraft attitude (roll, pitch, and yaw). This level of processing is designated GCS (geometric correction system) level 1. These data are not very accurate with respect to reference map coordinates. This is especially true in areas having precipitous topography, such as the Youghiogheny River valley. Terrain-induced imagery distortions are referred to as vertical displacement error and can be corrected only by utilization of a high-accuracy digital elevation grid acquired over the same area, in a process known as orthorectification. However, moderate improvements in the positional accuracy of these data were accomplished by manual selection of ground control points (GCPs). GCPs consist of features identifiable in the image and on a reference map of high-quality and known accuracy. The GCP coordinates and corresponding image coordinates are analyzed by a least-squares regression to determine coefficients for the transformation equations. These equations relate the ground coordinates extracted from the map with image coordinates. This process would normally be followed by a re-sampling operation to "warp" the imagery by displacing the pixels by the appropriate amount such that the pixels selected in the imagery are assigned the same geographical coordinates as the corresponding pixels in the reference map. When the data is successfully reprocessed this way, the imagery

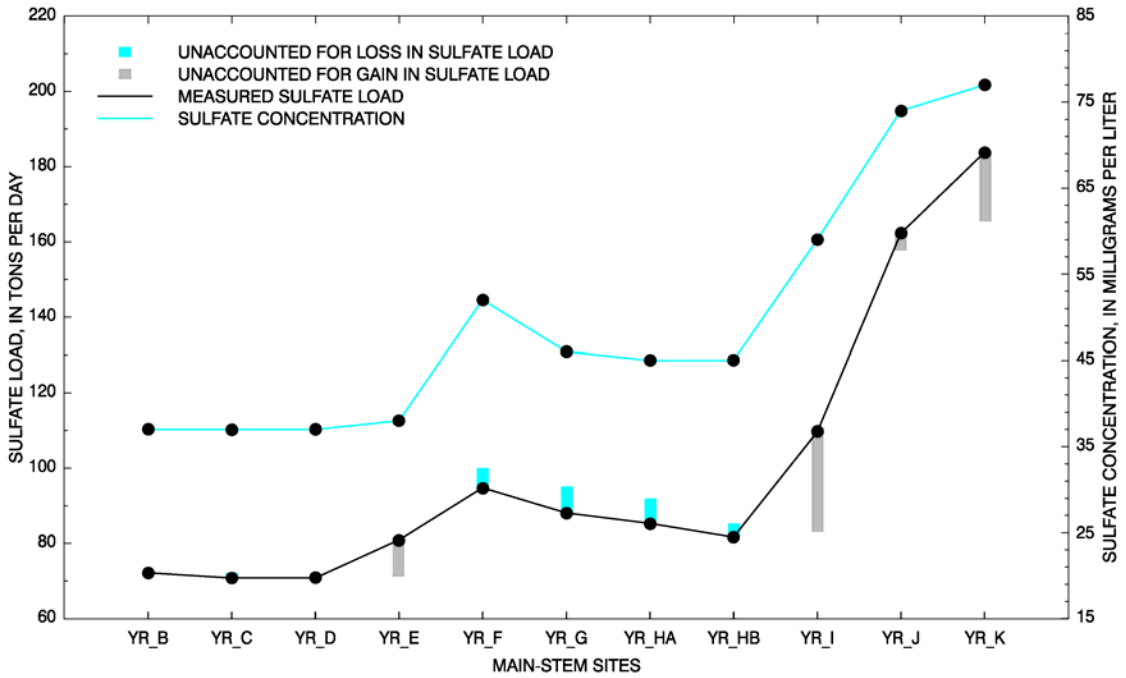

Figure 4. Measured sulfate loads and concentrations at mainstem sites during the synoptic survey in the Lower Youghiogheny River Basin, Pennsylvania, Oct 5-7, 1998. Unaccounted losses and gains are the result of subtracting the calculated sulfate load (the sum of the measured sulfate load at the closest upstream mainstem site plus the loads measured for any tributaries flowing into the reach) from the measured load at each site.

is co-registered spatially with respect to the reference map.

Data processing

The data-processing procedures were designed to separate land features from water features, particularly ground-water features such as mine drainage. As mine drainage discharges to the surface as a ground-water spring or seep, its temperature is characteristic of that of the local ground-water flow system. During winter months and early spring, ground water is warmer than surface streams, which are in turn warmer than the land surface. Processing of the TIR data resulted in a classified image that distinguished these features (Figure 5).

Feature Extraction

The reclassified imagery was processed using several models that were designed to filter and clean the reclassified data. This process was used to rapidly identify contiguous areas of similar pixels for converting the raster data into a polygon vector format. In vector format, each polygon was attributed with data fields for feature temperature classification code (1 = shallow surface water, 2 = deep channel flow, 3 = ground-water source), area (m^2), and a unique ID number for identification purposes. Selecting features for field review was completed through GIS data analysis. These procedures are described in detail in Sams and Veloski (2003). Seventy sites within the study area were identified as possible AMD sources.

Factors Affecting TIR Data

Remote-sensing images, acquired by multispectral scanners, satellite, or a photographic system from an airborne platform, are susceptible to a variety of geometric distortions. Motion of the multispectral scanner caused by the inherent instability of the airborne platform was addressed through the application of a geometric correction system based on inertial measurement data acquired along the route of flight. The altitude of the aircraft is seldom maintained at a precise elevation above ground level, especially in areas where terrain elevation fluctuates dramatically. Departures in flying altitude above ground level can affect the ground resolution of the resulting imagery. Fortunately, this was not a problem along the river channel because the helicopter flight path followed the Youghiogheny River, although the steep terrain above the river was affected. Relief displacement error also was present. Relief error is a distortion of the imagery that causes objects to appear elongated radially and away from the principal point along the ground track of the aircraft (nadir line) (Figure 6). The effects are most prevalent at the edge of the image and are exacerbated by sharply rising terrain above both river banks. These combined

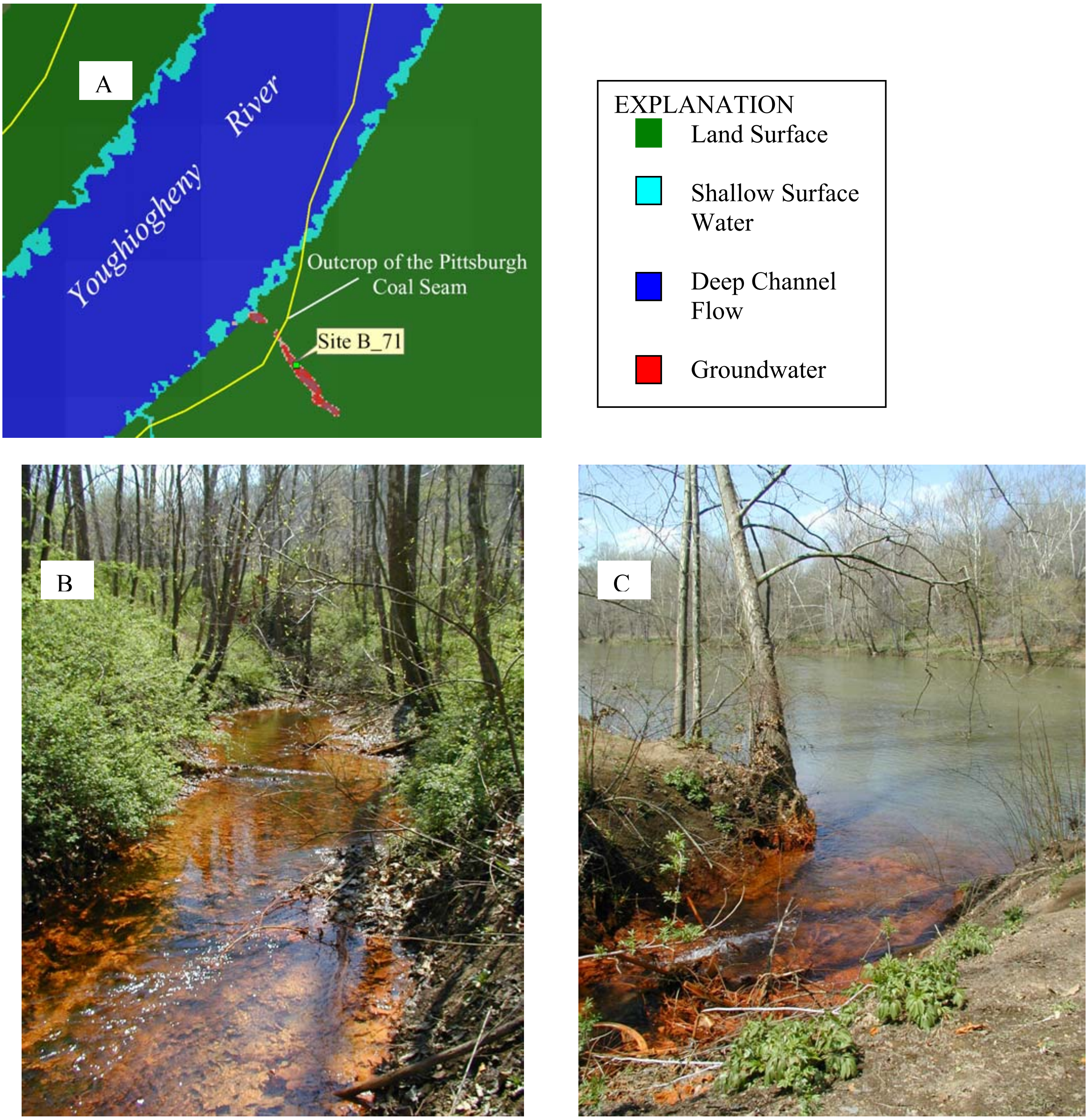

Figure 5. (A) Classified thermal infrared image of mine drainage site B-71, (B) digital picture of B-71 at source (outcrop of the Pittsburgh Coal Seam), (C) and picture of B-71 entering the Youghiogheny River

effects increase the positional error of features and the likelihood that certain objects will not be seen.

The effectiveness of TIR also may have been compromised by obstructions caused by the tree canopy. This was especially true for coniferous species of trees and other non-deciduous species such as mountain laurel. Furthermore, leaves of coniferous trees exhibit a relatively high radiant temperature because of thermal storage and unusual thermal emissive properties of the leaf cell structure (Sabins 1997). This property can interfere with the interpretation of thermal anomalies.

Field Verification

The 70 points derived from the TIR data in ESRI shapefile format were uploaded to handheld PDA-type computers equipped with Global Positioning System (GPS) navigation software (ESRI, Arcpad).

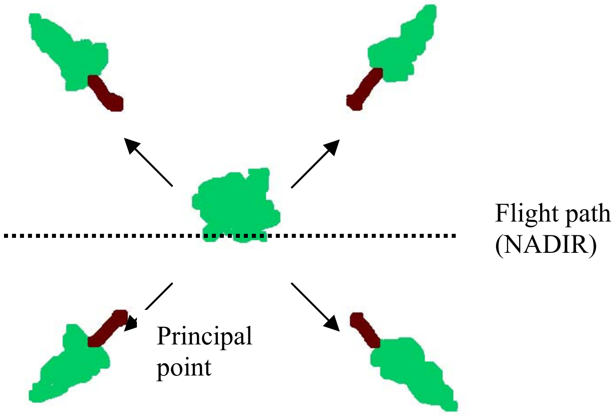

Figure 6. Relief displacement of features along a flight line

The navigation software is designed to receive the GPS data, which contain range and navigation information, in an ASCII readable format. This output is then translated into a position fix and rendered by the software into a moving map-type presentation for navigation purposes. A status line presents coordinate information that was used to navigate to any feature in the database. USGS Digital Ortho Quarter Quad (DOQQ) and USGS Digital Raster Graphic (DRG) were used as the base layers for the purpose of orientation. The 70 potential AMD sites selected from TIR data were plotted on top of the DRG or DOQQ basemap layer. In addition, color-enhanced data from each TIR flight line were converted to a compressed MrSID image (LizardTech, Inc.) for use on the PDA to view the raw imagery in the field and to confirm site locations. Data layers for roads and trails within the project area were used as part of the navigation system to minimize travel by foot. Information on site conditions along with field water-quality measurements from a YSI model 556 multi-parameter probe that included water temperature, pH, and specific conductance were collected at each site. Sites were classified as mine drainage if field pH was less than 4 or specific conductance was greater than 400 µS/cm. Ground water or springs unaffected by mining had near neutral pH and specific conductance less than 200 µS/cm. Most commonly, other evidence suggested the water was affected by mining, such as areas with extensive deposition of ferric-iron precipitates. Each site was photographed digitally.

Results and Discussion

Field Reconnaissance

Field checks were completed at all 70 sites identified in the TIR data (Figure 7) in approximately 5 days by a 2 person team. The 70 sites were classified into 6 categories based upon field inspection. The results are shown in Table 2. Twenty-four sites were classified

Table 2. Results of field reconnaissance of TIR sites

Site Type	# of Sites
Mine Drainage	24
Surface Pond	1
Undetermined	8
Wetlands	3
Spring	23
Stream	11
Total	70

as mine-drainage sites based on the field inspection. The high percentage of mine-drainage sites was expected based on the feature-extraction methods used. All of the mine discharges were within areas of the Pittsburgh Coal Seam (Figure 7). No mine discharges were identified outside of this area (Dawson to Smithton).The eight sites classified as undetermined were those that had no obvious heat source in the field to distinguish it from the background land surface. These transient heat sources could be areas of high animal density, because the region supports a dense deer population.

Water Quality

Data from the USGS/DOE water-quality survey in 1998 were used to complete a mass balance of sulfate loads for the Lower Youghiogheny River from Connellsville to McKeesport. In this 1998 survey, most of the unaccounted-for gains in sulfate loads were between Smithton and McKeesport (Figure 8). In this 40-km stretch of the river, 11 mine discharges were identified from the TIR data. Five of the mine discharges were between Smithton and West Newton, where a sulfate load of 25 t/day entered the river and was not accounted for through the chemical mass balance data from the 1998 survey. A large mine discharge (site B-17) (Figure 9) enters the river about 8 km downstream from Smithton and could account for this difference in the mass balance. Six of the mine discharges were identified in the river reach between Sutersville and McKeesport. A sulfate load of 18 tons/day entered the river and was not accounted for in the 1998 chemical mass balance. Two of those six mine discharges were identified as site B-2 and site B-8 (Figure 10) from the TIR data. The river reach between West Newton and Sutersville had no mine discharges identified from the TIR data and almost the entire sulfate load was accounted for. This reach had the largest increase in sulfate loads. Sewickley Creek enters the Youghiogheny River just upstream of Sutersville and contributes 49 t/day or 45% of the sulfate load to the river.

An additional water-quality survey would need to be conducted between Smithton and McKeesport to determine if the 11 mine discharges identified from

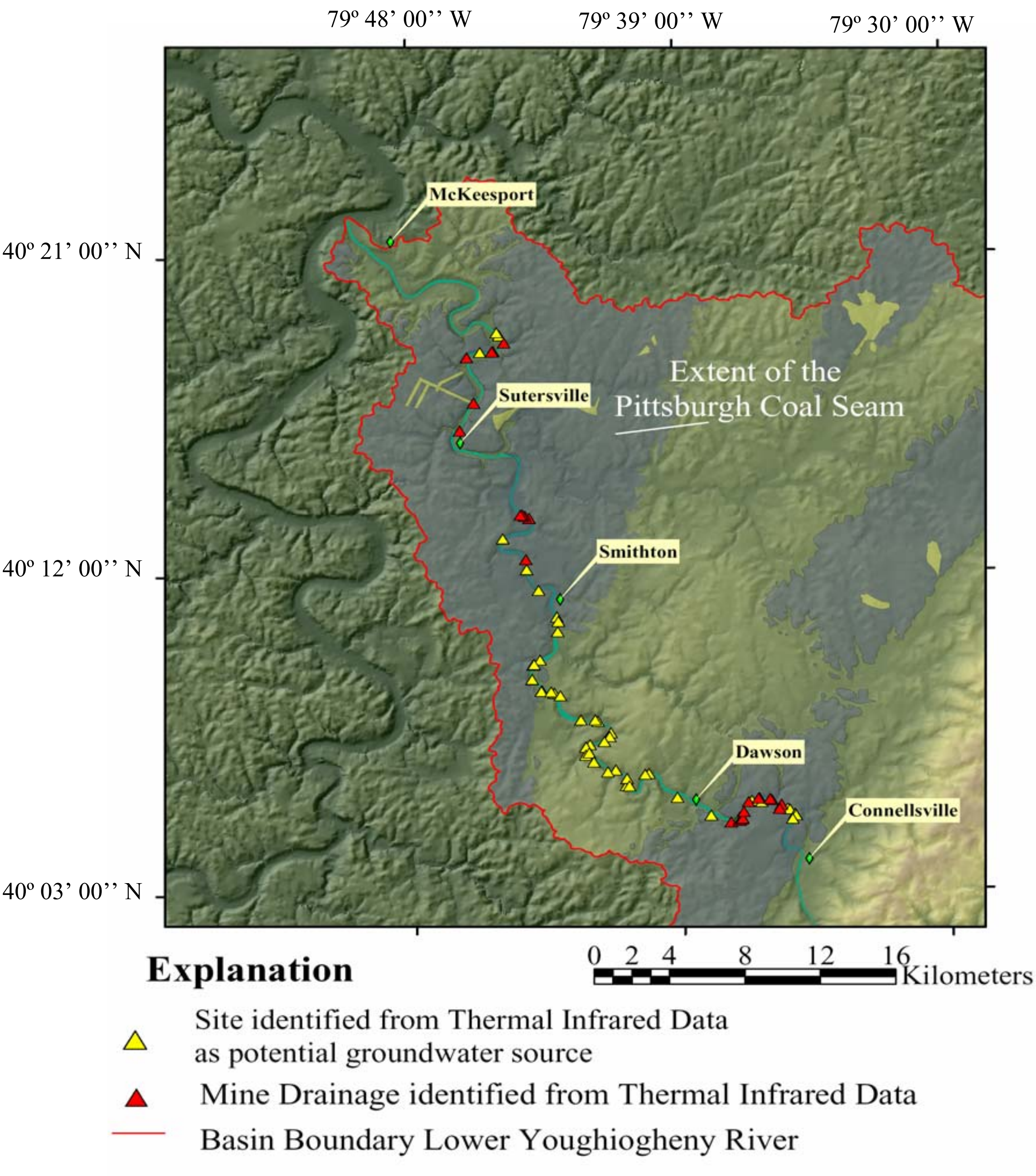

Figure 7. Location of sites identified from thermal infrared data

the TIR data were responsible for the remaining 43 t/day of sulfate load entering the Youghiogheny River that were not accounted for through the chemical mass balance data from the 1998 survey.

Summary

Nighttime high-resolution (1 m^2) airborne thermal infrared imagery (TIR) data were collected in the predawn hours during Feb 5-8 and March 11-12, 1999, from a helicopter platform along 72.4 km of the mainstem of the Youghiogheny River from Connellsville to McKeesport in southwestern Pennsylvania to map potential sources of mine drainage. Prior to this investigation, very little detailed mapping of mine-drainage sites was available for the study area. In 1998, a detailed water-quality survey of the Lower Youghiogheny River conducted by the USGS and the DOE was successful in identifying reaches of the Youghiogheny River where unaccounted-for loads of constituents associated with mining activities, in particular, sulfate, were entering the river based on a water quality mass balance. However, the survey was not

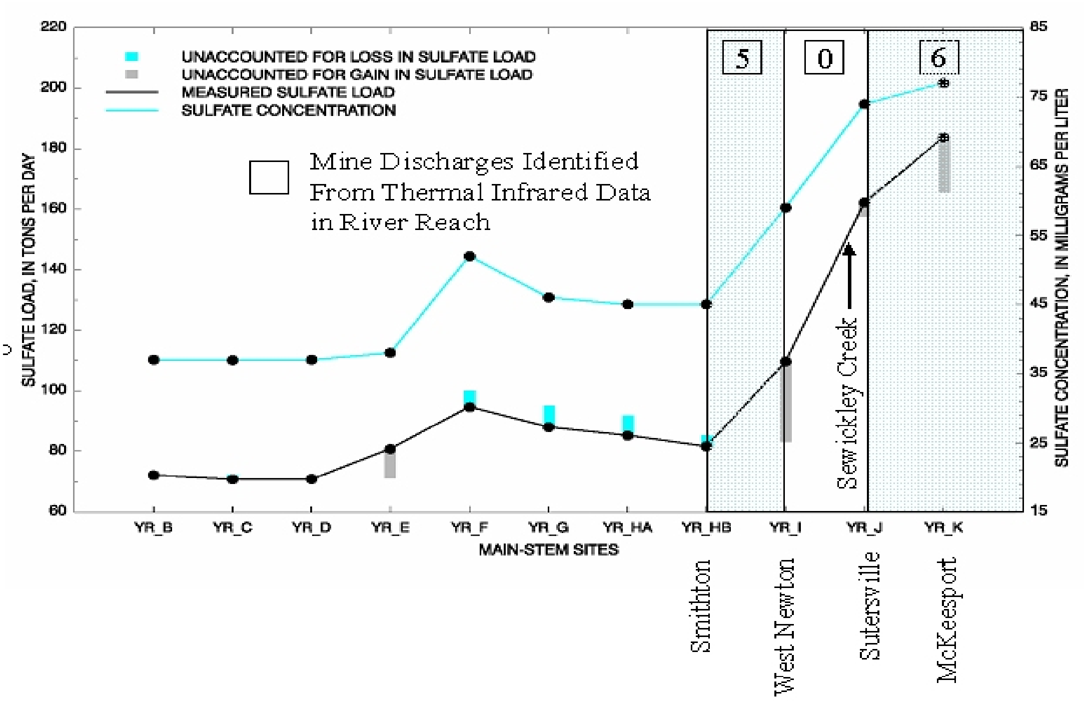

Figure 8. Mine drainage sites identified from TIR data and their relative location within a river reach section of the lower Youghiogheny River, showing the effects of sulfate loads and concentrations. Unaccounted (until now) losses and gains in sulfate load are indicated by bars on the lower (sulfate load) line.

Figure 9. View of mine discharge B-17, 6 m upstream from the confluence with the Youghiogheny River, within the river reach Smithton to West Newton

able to pinpoint the sources of the contamination (Sams et al. 2001). Had the concept of applying TIR technology to the environmental problems associated with the Youghiogheny River been developed prior to the 1998 study, that study would have been much more efficient, accurate, and complete.

This investigation evaluated the effectiveness of TIR for identifying sources of AMD from abandoned mines that discharge directly to the main-stem of the Youghiogheny River. Potential AMD sources were extracted from the TIR data employing custom

Figure 10. View of significant mine discharge sites B-2 and B-8 identified from TIR data within the Sutersville to McKeesport section of the Youghiogheny River

image-processing algorithms combined with a simple GIS data analysis. Seventy sites were identified within the study area as possible AMD sources. The point coverage and associated attributes were uploaded to PDA computers utilizing GPS input to provide moving map navigation for accurately locating sites during the reconnaissance phase of this investigation. Field observations and measurements of pH, specific conductance, and temperature were used to differentiate between ground water contaminated by AMD and natural springs. The field review was completed in approximately 5 days by a 2-person team. Twenty-four sites were classified as mine-drainage sites based on the field inspection. All of the mine discharges were within the mined areas of the Pittsburgh Coal Seam. No mine discharges were identified outside of this area. In the 40-km reach of the river between Smithton and McKeesport, 11 such mine discharges were identified. These data support the hypothesis that unaccounted-for discharges were contributing to the sulfate loadings, as suggested from the 1998 synoptic water-quality survey.

Today, government agencies and local conservation groups and watershed associations are developing plans to correct environmental problems such as mine drainage. The success of remediation plans hinges on the complete knowledge of all pollution sources within a watershed area. Methods to reduce costs and improve efficiencies in detection of mine drainage sites on a watershed scale, such as remote sensing, are needed.

Disclaimer: The use of commercial products and brand names is intended to facilitate understanding and does not imply endorsement by either the USGS or the DOE**.**

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